TRANSTIBIAL AMPUTEE GAIT ANALYSIS: A COMPARISON OF TWO TYPES OF PROSTHETIC FEET

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Abstract- **This study was performed as a case study on one unilateral transtibial traumatic amputee. The purpose was to determine whether a single-axis prosthetic foot enhanced gait as opposed to a SACH prosthetic foot when walking on uneven ground. Three-dimensional gait analysis was used to study gait kinematics using the two prosthetic feet on three different walkways: wood, sand and pebbles. The kinematic variables stride length, cadence, speed, stride time, prosthetic stance and normal stance as well as joint relative angles were used in the analysis. The results confirmed the asymmetry of amputee gait. With both prosthetic feet, the amputee walked with a lower speed, cadence and stride length on both types of uneven ground than on the flat ground. The single-axis foot was found to significantly increase speed and cadence, and to affect hip and knee flexion angles. However, there was no clear conclusion that one foot performed better on all walkways.**
Keywords- prosthetic foot, gait analysis, uneven ground

I. INTRODUCTION

The gait of transtibial (below knee) amputees differs significantly from normal gait [1, 2]. The choice of artificial or prosthetic components affects amputee gait so the selection of suitable components for each case is a challenge for prosthetists. The aim is always to provide the amputee with as normal a gait as possible in addition to safety and stability with the minimum financial cost to the amputee. There are many different prosthetic foot and ankle mechanisms available on the market today. In order to facilitate and optimize the selection process, many studies have been published comparing two or more of these prosthetic feet [1, 3, 4, 5, 7, 8]. Reference [6] is comprehensive review of the literature.

Comparison and evaluation studies of prosthetic feet have used two-dimensional (2-D) [2, 5, 7, 9] and three dimensional (3-D) gait analysis [1, 8] systems for data acquisition. The kinematic variables: speed, cadence, stride time, stride length as well as prosthetic (P) and normal (N) stance times have been the most frequently used. In addition, the hip, knee and ankle joint angles have been recorded for both the P and N sides.

This study was performed as a case study on one unilateral transtibial traumatic amputee. The amputee had been wearing a SACH (solid ankle cushioned heel) foot for 21 years. The amputee expressed the desire for a more active lifestyle and the ability to walk on uneven terrain. It was decided to fit her with a single-axis (SA) prosthetic foot (Otto Bock). The term single-axis refers to prosthetic feet with a single hinge in the direction of motion that provides plantar flexion and dorsiflexion [6], as opposed to SACH feet which are non-articulated at the ankle. 3-D gait analysis was used to investigate whether the single-axis prosthetic foot enhanced gait as opposed to the SACH prosthetic foot when walking on uneven terrain.

II. METHODOLOGY

A) Subject: The amputee was a 26 year old female whose right leg was amputated traumatically below the knee at the age of 5 years. Her pelvis was tilted on the right side. She also had an internal rotation in her right knee due to the accident. She was currently fitted with a SACH foot. It was decided to fit and test her with a single-axis (SA) prosthetic foot (Otto Bock). The subject was 160 cm high and weighed 58 kg.

B) Protocol: All experiments and measurements were first performed with the amputee's own SACH foot. The amputee was then fitted with the new SA foot by a certified prosthetist and used it for two weeks prior to repeating all measurements. This was an adaptation period to allow the amputee to feel comfortable and confident to walk with the new foot. For each foot, the measurements were repeated while the amputee walked on three different types of grounds: a flat wood walkway, a sand walkway and a pebble walkway. These walkways were selected as a representation of different and uneven terrains the amputee can encounter in her daily life. Starting with the wood walkway, the amputee was asked to walk repeatedly at a self-selected normal walking speed to the end of the walkway and back. The walkway was 1.2 m wide and 6.5 m long allowing her to walk five complete gait cycles. Measurements were not taken until the second time she started the walkway. Each length of walkway is termed a trial. The measurements where then taken repeatedly for 12 to 14 trials after which the amputee was allowed to rest. The same protocol was repeated for the two other walkways with the subject wearing the SACH foot, then two weeks later with the SA foot. 3-D gait analysis was performed using a 3-D Qualisys motion analysis system. Twenty passive reflective markers were placed bilaterally on bony landmarks on the pelvis and lower extremities on both the right (R) prosthetic (P) and left (L) normal (N) sides and captured by six high speed infrared cameras (120 frames/sec). The measurements were used to calculate the kinematic variables: speed, cadence, stride time, stride length, L stance, R stance as well as joint (hip, knee and ankle) angles for both

the P and N sides. Data reduction and analysis were performed using Qualisis software.

III. Results

For all gait measurements, the mean of a minimum of eleven successful trials was taken. Table 1 shows the means and standard deviations (sd) of each of the kinematic variables for the SACH foot and the SA foot on the three walkways: wood, sand and pebbles. The results show that on all walkways, the stance phase of the N limb is longer than that of the P limb for both the SACH and SA feet, with mean values of 66% and 62% respectively. Statistical analysis using SPSS was performed on all kinematic variables and the *p*-values showed the following: For the wood walkway, there was a significant ($p < 0.01$) difference between the SACH and SA feet in speed, N stance and P stance. For the sand walkway, there was a significant difference between the SACH and SA feet in cadence, speed, stride time and P stance. For the pebble walkway, there was a significant difference between the SACH and SA feet in cadence and stride time.

The self-selected walking speed of the amputee averaged 0.99 m/s with the SA foot while the corresponding value was 0.9 m/s with the SACH foot, even though the subject had been asked to maintain a constant speed for all trials. The mean cadence with the SA foot was 108.02 steps/min while the corresponding value was 100.27 steps/min with the SACH foot. Thus when the variables were averaged over the three walkways, the SA foot showed greater values of cadence (7.7%), and speed (9.3%) over the SACH foot, and smaller values of stride time (6.2%). However, the type of foot did not have a significant effect on stride length.

The statistics also showed that for each foot there was a highly significant difference in all kinematic parameters between the three walkways. Gait on the wood walkway showed greater mean values for the stride length, cadence, and speed as compared to those obtained for the pebble or sand walkways. The self-selected walking speed of the amputee averaged 1.13 m/s for the wood, while it was 1.01 m/s and 0.81 m/s for the sand and pebble walkways respectively. The mean stride time on the wood was shorter (1.08 s) than those obtained for the sand and pebble walkways (1.15 s and 1.25 s respectively).

Representative graphs comparing P (right) and N (left) knee flexion angles for the wood walkway are shown in Fig. 1 for the SACH foot and in Fig. 2 for the SA foot. The angle is expressed as a percentage of the gait cycle. The graphs show that the knee flexion angle of the P limb is significantly reduced in early stance. This observation is the same for both prosthetic feet on the three walkways. In addition, the maximum knee flexion angle and the range are both smaller for the P limb than for the N limb. However, walking with the SA foot produced larger maximum P (68.3^o) and N (72.2^o) flexion angles than with the SACH foot P (57.5^o) and N (65.8^o).flexion angles. The hip flexion angles for the wood walkway are shown in Fig. 3 and Fig. 4 for the SACH and SA foot respectively. They show that walking with the SA foot allows larger maximum P (29.6^o) and N (36.1^o) flexion angles than with the SACH foot P (22.9^o) and N (24.8^o).

The range of motion (ROM) defined as the difference between the minimum and maximum angles for each of the hip, knee and ankle joints was computed in each case and the mean values are listed in Table 2. A symmetry index (SI) was computed for the ROM data in order to quantify gait asymmetries and the results are also listed in Table 2. The SI is defined as the ROM of one limb divided by the ROM of the contralateral limb [7].

Table 1.
Results of kinematic variables mean ±sd for two prosthetic feet

Walkway	Variable	SACH	Single-Axis	*p*-value
Wood	1- Stride Length (m)	1.19 ±0.04	1.21 ±0.04	0.275
	2- Cadence (steps/min)	112.1 ±2.76	112.57 ±2.99	0.613
	3- Speed (m/s)	1.09 ±0.022	1.14 ±0.049	0.001
	4- Stride Time (s)	1.084 ±0.037	1.071 ±0.046	0.346
	5- P Stance (% gait cycle)	62.47 ±0.84	61.57 ±1.56	0.032
	6- N Stance (%gait cycle)	63.5 ±1.02	65 ±1.20	0.000
Sand	1- Stride Length (m)	1.1 ±0.04	1.11 ±0.06	0.508
	2- Cadence (steps/min)	95.5 ±4.05	110.1 ±2.42	0.000
	3- Speed (m/s)	0.87 ±0.04	1.01 ±0.06	0.00
	4- Stride Time (s)	1.2 ±0.06	1.1 ±0.00	0.00
	5- P Stance (% gait cycle)	61.3 ±2.16	59.9 ±1.03	0.039
	6- N Stance (%gait cycle)	66.57 ±3.27	66.73 ±1.91	0.871
Pebbles	1- Stride Length (m)	0.94 ±0.05	0.96 ±0.1	0.625
	2- Cadence (steps/min)	93.2 ±6.22	101.4 ±1.12	0.029
	3- Speed (m/s)	0.75 ±0.07	0.81 ±0.132	0.24
	4- Stride Time (s)	1.3 ±0.09	1.2 ±0.118	0.046
	5- P Stance (% gait cycle)	64.7 ±3.34	63.6 ±2.69	0.377
	6- N Stance (%gait cycle)	68.1 ±2.1	67.15 ±2.96	0.388

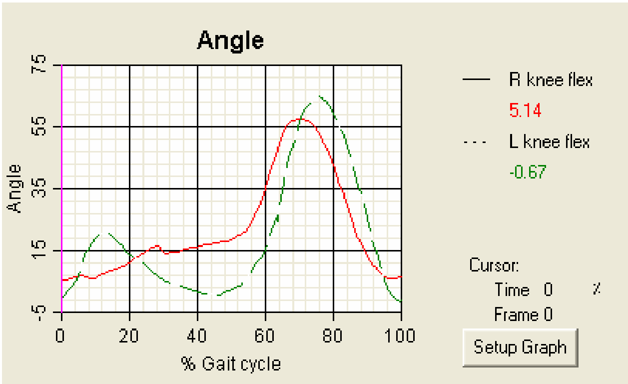

Fig. 1. Knee flexion angle on the wood walkway using the SACH foot

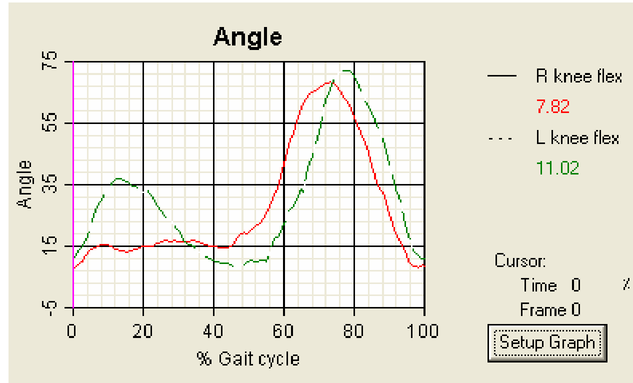

Fig. 2. Knee flexion angle on the wood walkway using the SA foot

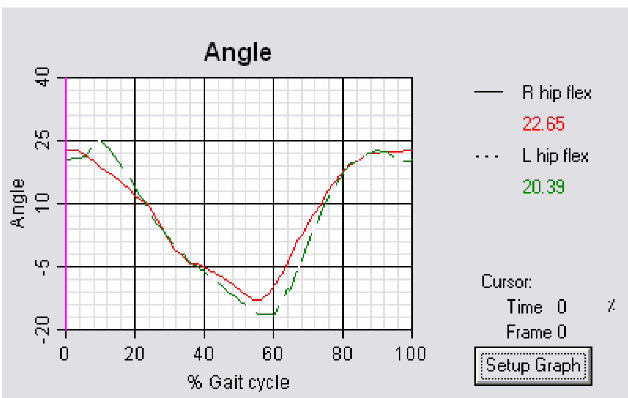

Fig. 3. Hip flexion angle on the wood walkway using the SACH foot

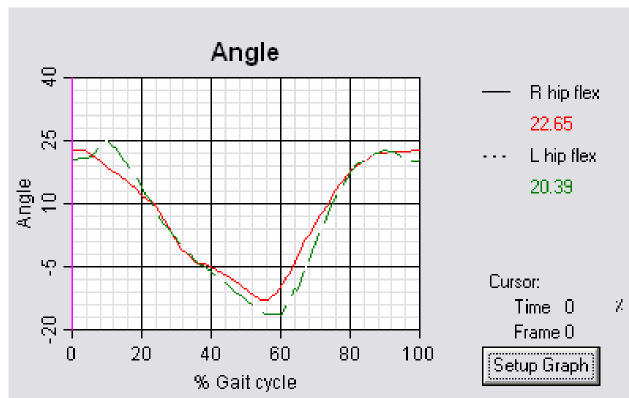

Fig. 4. Hip flexion angle on the wood walkway using the SA foot

Table 2. Results of ROM mean ±sd and SI

Joint	Walkway	SACH		S.I.	Single -Axis		S.I.
		Prosthetic (R)	Normal (L)		Prosthetic (R)	Normal (L)	
Hip	Wood	37 ±1.67	39 ±1.23	0.948	41 ±3.63	49 ±1.76	0.836
	Sand	46 ±1.67	53 ±2.40	0.867	49 ±1.4	52 ±3.12	0.942
	Pebbles	36 ±1.88	42 ±1.96	0.857	42 ±3.54	57 ±4.01	0.736
Knee	Wood	53 ±2.02	63 ±2.72	0.841	58 ±1.86	65 ±2.30	0.892
	Sand	64 ±4.89	72 ±3.29	0.888	67 ±2.63	67 ±4.49	1
	Pebbles	52 ±3.81	63 ±2.99	0.825	54 ±4.81	75 ±2.47	0.72
Ankle	Wood	16 ±3.56	36 ±8.61	0.444	17 ±4.52	28 ±10.19	0.607
	Sand	17 ±1.37	33 ±2.65	0.515	25 ±2.32	31 ±2.7	0.806
	Pebbles	25 ±4.19	26 ±5.57	0.961	21 ±4.74	23 ±2.48	0.913

IV. Discussion

This study investigated the effect of the type of prosthetic foot on the kinematics of transtibial amputee gait for three different types of walkways. The results showed a general asymmetry of prosthetic gait, confirmed by the SI, and are consistent with previous studies [6, 7, 9]. For both the SACH and SA feet, the stance phase of the N limb is longer than that of the P limb on the three walkways. This has previously been reported [5, 6, 9, 10, 12] and is due to the tendency of the amputee to spend more time on the N limb to improve stability. As a result, the swing phase of the P limb is longer than the swing phase of the N limb.

Another general result is that the knee flexion angle of the P limb does not have two peaks like that of the N limb, indicating that the knee remains relatively extended at early stance.

The type of prosthetic foot was found to have a highly significant effect on cadence, speed, and stride time. The SA foot showed greater values of cadence and speed over the SACH foot, and smaller values of stride time. However, the type of foot did not have a significant effect on stride length. The self-selected walking speed of the amputee was significantly faster with the SA foot than with the SACH foot, even though the subject had been asked to maintain a constant speed for all trials. Thus the SA foot facilitated faster walking speeds as compared to the SACH foot. Such findings are in agreement with those obtained by other investigators [10, 11].

The SA foot allowed higher values of the maximum hip flexion angle just before heel strike, as well as higher mean hip joint ROM for the two limbs as compared to the SACH foot. For the P limb they were 43.7º and 39.5º for SA and SACH feet respectively, while for the N limb they were 52.8º and 44.7º respectively. Results indicated also that the mean value of the knee joint ROM of the N limb (67.5º) was greater than that attained by the P limb (57.9º). In addition, the SA foot allowed higher values of the knee joint ROM on the P side as compared to the SACH foot. However the SI did not show that the SA foot consistently improved gait symmetry on all walkways.

Foot-floor contact is a dominating factor in gait. Floor characteristics have been shown to affect the force/moment reactions at both the ankle and knee joints significantly [10]. This suggested that floor characteristics might also affect the kinematic gait parameters. The results of this study showed a highly significant effect of the type of walkway on stride length, cadence, speed, stride time, and stance values for both limbs. Gait on the wood walkway showed significantly greater mean values for the stride length, cadence, and speed as compared to those obtained for the pebble or sand walkways. These results indicate that it was more difficult for the amputee to walk on the two uneven walkways.

Results obtained for the range of motion illustrated a highly significant effect of walkway type on the ROM of the hip and knee joints. The mean values of the hip ROM were 49.8º, 44.3º, and 41.4º for the sand, pebble, and wood walkways respectively, while the corresponding ROM values obtained for the knee were 67.4º, 60.9º, and 59.7º respectively.

V. Conclusion

The increase of the N limb stance over that of the P limb confirms the fact that transtibial amputees tend to shorten the P single limb support time, and lengthen the N single limb support time in order to improve stability and comfort. The SA prosthetic foot was found to offer some advantages over the SACH foot including increased walking speed and cadence. It also consistently allowed a larger hip ROM. Floor characteristics appeared to be a dominant factor that significantly affected the gait parameters of the amputee. Using either prosthetic foot, the amputee walked with a slower self-selected speed and a smaller stride length on the uneven walkways (sand and pebbles).

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